NOWCAST/FORECAST System for Coastal/Open Ocean Regions

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LONG-TERM GOALS

To develop and evaluate a nowcast/forecast system for coastal/open ocean regions with the Hybrid Coordinate Ocean Model (HYCOM). To make HYCOM a truly all-purpose generalized coordinate ocean model that can be used in all ocean environment.

OBJECTIVES

a) To evaluate the model's performance in reproducing the oceanic circulation, with a special focus on the coastal regions;

b) To refine the hybrid coordinate design of the ocean model, especially in shallow coastal regions.

c) To evaluate the model's forecast skills and usefulness in providing boundary conditions for ultra fine-mesh coastal models;

APPROACH

A series of numerical models of increasing complexity and resolution is used to (a) evaluate the hybrid coordinate design of the model, (b) develop an understanding of the interaction between the ocean interior and the coastal regions, and (c) evaluate the model's forecast skills.

WORK COMPLETED

a) Inclusion and evaluation of four vertical mixing schemes in HYCOM 2.1 (Halliwell, 2002);

b) Evaluation of the hybrid coordinate (Chassignet et al., 2002);

c) Development and testing of advection schemes (Iskandarani and Chassignet, 2002) ;

e) Data assimilation capabilities for HYCOM;

f) Several process studies on boundary currents, gyre dynamics, and overflows (Stern and Chassignet, 2000; Pratt et al., 2000; Ozgokmen et al., 2001; Ozgokmen and Chassignet, 2002).

RESULTS

HYCOM 2.1 was recently released (September 2002) and is the result of collaborative efforts between the Naval Research Laboratory (Wallcraft), the University of Miami (Halliwell, Chassignet), and the Los Alamos National Laboratory (Bleck). The hybrid coordinate is one that is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to pressure-level coordinates in the mixed layer and/or unstratified seas. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models, such as NLOM and MICOM, toward shallow coastal seas and unstratified parts of the world ocean. The hybrid model maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics. The capability of assigning additional coordinate surfaces to the oceanic mixed layer in HYCOM gives us the option of implementing sophisticated vertical mixing turbulence closure schemes. Halliwell (2002) evaluated the vertical mixing algorithms embedded in HYCOM using low-resolution climatological simulations of the Atlantic Ocean. Thirteen model experiments were analyzed involving different combinations of vertical mixing algorithms, vertical coordinate choice, and vertical resolution. The basic set of eight experiments was run with 22 vertical layers. Seven of these were run with hybrid vertical coordinates to evaluate sensitivity to vertical mixing choice while the other was run with isopycnic coordinates (MICOM mode) to determine sensitivity to vertical coordinate choice. To complete the set of experiments, five of the 22-layer experiments were re-run with 32 vertical layers to evaluate the impact of vertical resolution.

The full set of vertical mixing options contained in the latest version of HYCOM (version 2.1) includes six primary vertical mixing algorithms, of which two are non-slab models and four are slab models. The two non-slab models govern vertical mixing throughout the water column and are the nonlocal K-Profile Parameterization model of Large et al. (1994) (KPP), and the level 2.5 turbulence closure algorithm of Mellor and Yamada (1982) (MY). The slab models include the dynamical instability model of Price et al. (1986) (PWP) and three versions of the Kraus-Turner model. There are two versions of the Kraus-Turner model to be used with hybrid vertical coordinates: an accurate (but relatively inefficient) version (KTA) along with a simplified (less accurate, but more efficient) version (KTB). The KTB model was used in the global simulation of Bleck (2002). A third version of the Kraus-Turner model (KTC) obtained from MICOM 2.8 is used when the model is run with isopycnic vertical coordinates only (MICOM mode). Since the four slab models govern only mixed layer entrainment and detrainment, three interior diapycnal mixing algorithms are also included in HYCOM to supplement these mixed layer models. Two of these are designed for use with hybrid vertical coordinates, an explicit (MICOM-like) model and an implicit (KPP-like) model. Implementation of these vertical mixing algorithms in HYCOM required the addition of penetrating shortwave radiation and of an implicit solution algorithm for the vertical diffusion equation.

The climatological Atlantic simulations using 22 vertical layers demonstrate that very similar results are obtained using four of the mixing algorithms with hybrid vertical coordinates: KPP, MY, PWP, and KTAIP (with “I” signifying implicit interior diapycnal mixing and “P” signifying penetrating shortwave radiation). All four of these experiments used penetrating shortwave radiation. Fields simulated using other vertical mixing schemes (KTA without penetrating shortwave radiation (experiments KTAI and KTAE, where “E” signifies explicit diapycnal mixing), KTBI, and MICOM mode) display comparatively large differences from the other four mixing choices. Some of the largest differences between MICOM mode simulations and hybrid coordinate simulations with models KPP, MY, PWP, and KTA exist in the upper 300 m of the water column between about 10S and 25N (Figure

1). In this region, the surface layer of warm, low-density water is substantially thinner in MICOM mode than it is in the four hybrid coordinate cases. Comparison with climatology indicates that the true thickness of the warm layer is in the middle of these two extremes. About half of this difference can be attributed to the lack of penetrating shortwave radiation (KTAIP versus KTAI in Figure 1) and to the absence of shear instability mixing (KTAI versus KTAE in Figure 1). Vertical mixing in hybrid case KTAE most closely resembles vertical mixing in MICOM mode. Penetrating shortwave radiation also exerts a large influence on subtropical mode water properties between 25 and 40N (KTAIP versus KTAI in Figure 1). The ability to include these two processes is a clear advantage of hybrid versus isopycnic models. Model simulations display equal or greater sensitivity to increasing vertical resolution than to changing vertical mixing algorithms. It is not possible to statistically identify the best vertical mixing scheme among KPP, MY, PWP, and KTAIP because differences among these fields are much smaller than differences between simulated and observed fields. Determination of the best hybrid mixing algorithms must await high-resolution simulations driven by realistic atmospheric forcing that resolves synoptic and diurnal time scales.

Model performance was also evaluated through inspection of one-dimensional profiles of thermodynamical variables and momentum. Upper-ocean profiles of T and S are shown for KPP mixing, MY mixing, and MICOM mode at a grid point in the Caribbean Sea within the Trade Wind belt (Figure 2). Close inspection of profiles above the mixed layer base reveals that weak vertical gradients do exist within the non-slab mixed layers in contrast to the homogenized slab profile for MICOM mode. Both non-slab models produce very similar profiles of all three variables that differ substantially from the MICOM-mode profiles. These differences suggest that the two hybrid-coordinate non-slab mixing schemes are more diffusive beneath the mixed layer base than the MICOM-mode mixing. Very sharp jumps are present at the MICOM mode mixed layer base while more gradual changes are present near and below the mixed layer base in the two non-slab mixing cases. Analyses presented in Halliwell (2002) reveal that in the tropical and subtropical Atlantic, the MICOM-mode run is not diffusive enough beneath the mixed layer, while the hybrid coordinate cases tend to be somewhat too diffusive. Both the lack of penetrating shortwave radiation and the absence of shear instability mixing beneath the mixed layer contribute to the insufficient diffusivity of the MICOM-mode. The cause of the enhanced diffusivity of hybrid vertical coordinates is under investigation, but it does not appear to have a large negative influence on the simulated basin-scale circulation.

The use of non-slab vertical mixing models permits HYCOM to resolve both geostrophic shear and the shear of the ageostrophic wind-driven flow. With the model driven by slowly varying monthly climatological wind stress, a well-defined Ekman spiral is observed at the Caribbean grid point (Figure 2) for both KPP and MY mixing. (The model was run with 32 layers to clearly resolve the vertical structure.) These velocity plots are generated by first identifying the model layer located at the base of the Ekman layer. In each case, this reference layer is easily identified by visual inspection of velocity vectors in each layer. The velocity in the reference layer is subtracted from the velocity in each layer above, and then these velocity difference vectors are plotted (Figure 2). In all cases, a well-developed Ekman spiral is present with good qualitative similarity observed between KPP and MY mixing. Although geostrophic velocity shear is present in all of these cases, it is clearly overwhelmed by the vertical shear of the ageostrophic wind driven flow. The MY Ekman layer is thicker than the KPP Ekman layer because the MY model produces larger viscosity values.

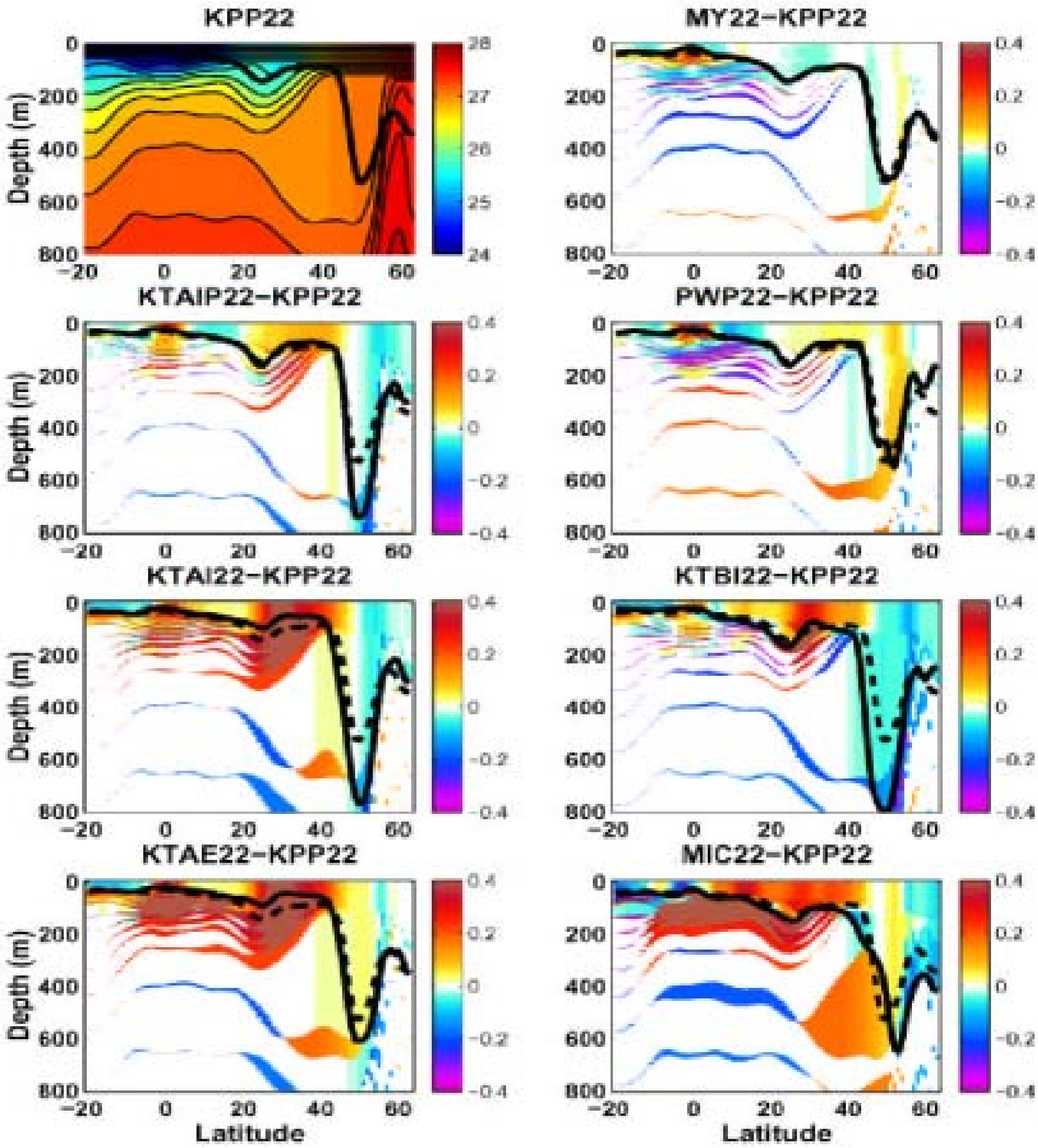

Figure 1. Winter 29W cross-section of s_0 for experiment KPP22 along with difference sections between the seven other 22-layer experiments and KPP22. In the isopycnic coordinate interior, differences are almost entirely the result of changes in interface depth. Above the isopycnic interior, "continuous" horizontal differences within layers become dominant. The thick solid lines are the mixed layer base for each experiment while the thick dashed lines in the difference sections are the KPP22 mixed layer base. Warm colors mean that the second experiment is denser than KPP22.

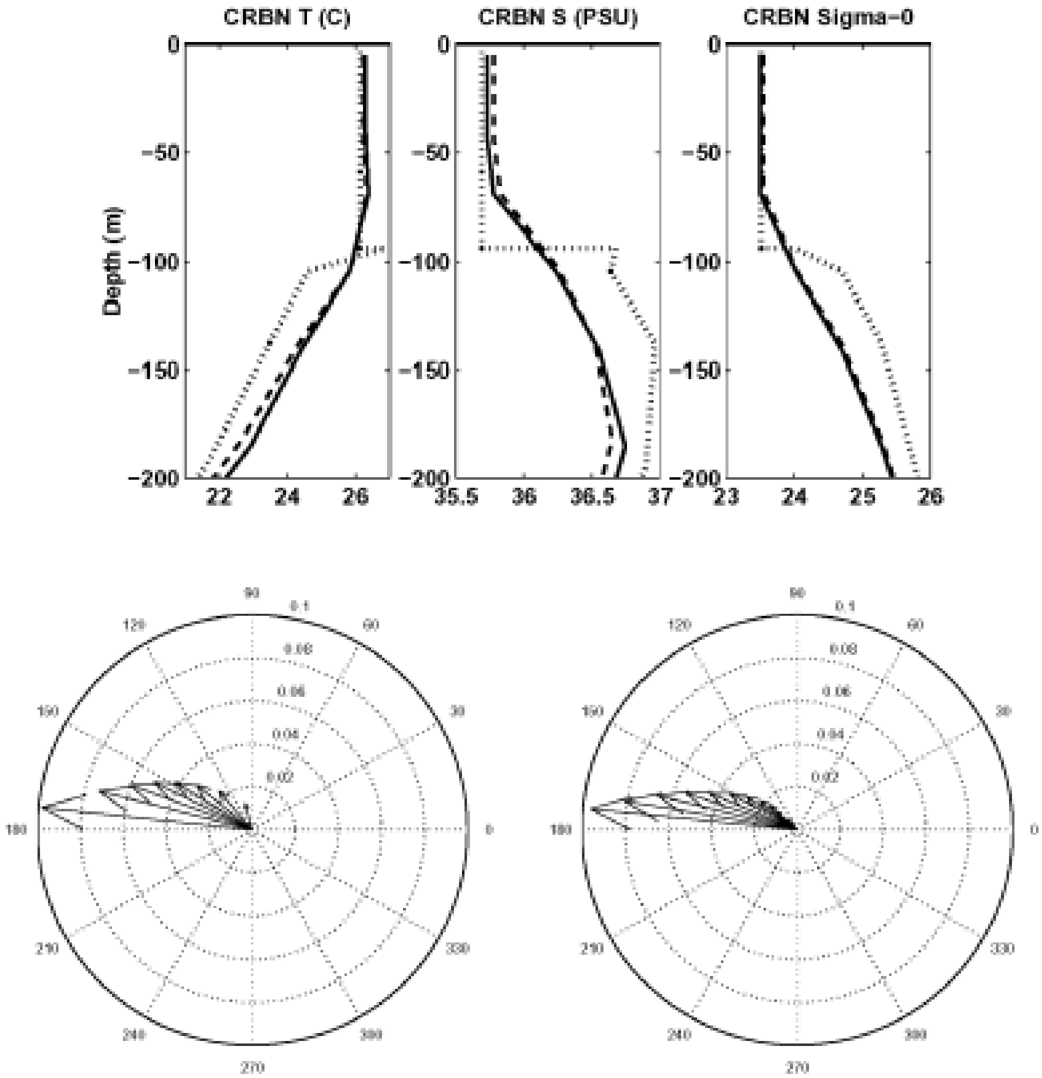

Figure 2. Profiles of T, S, and sigma-0 for winter (top panels) at a grid point in the Caribbean Sea (Trade Wind belt). Profiles are shown for KPP mixing (solid line), Mellor-Yamada 2.5 mixing (dashed line), and a MICOM mode (dotted line). Also shown are velocity vectors above a reference layer chosen by inspection to reside at the base of the Ekman layer for KPP mixing (bottom left) and Mellor-Yamada 2.5 mixing (bottom right). The reference layer velocity has been subtracted from the vectors shown. The central depth reference layers is 48 m for KPP mixing and 67 m for MY mixing, the later being deeper because MY mixing generates larger viscosity at this grid point.

The implementation of the generalized coordinate in HYCOM (Bleck, 2002) follows the theoretical foundation set forth in Bleck and Boudra (1981) and Bleck and Benjamin (1993): i.e., each coordinate surface is assigned a reference isopycnal. The model continually checks whether or not grid points lie on their reference isopycnals and, if not, attempts to move them vertically toward the reference position. However, the grid points are not allowed to migrate when this would lead to excessive crowding of coordinate surfaces. Thus, vertical grid points can be geometrically constrained to remain at a fixed depth while being allowed to join and follow their reference isopycnals in adjacent areas. As stated above, the default configuration in HYCOM is one that is isopycnal in the open stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions and to z-level coordinates in the mixed layer and/or unstratified seas. Thus, the model combines the advantages of the different types of coordinates in optimally simulating coastal and open-ocean circulation features. It is however left to the user to define the geographical regions in which any of the three coordinate choices is to be applied. It is possible for the user to run the model with purely z coordinates, purely sigma coordinates, or isopycnic coordinates (MICOM mode).

In Chassignet et al. (2002), the hybrid model's performance is evaluated by comparison to observations and to previous simulations configured for the North and Equatorial Atlantic. Building on past studies with the Community Modeling Experiment (CME) configuration (Chassignet et al., 1996; Smith et al., 2000), we examined the effect of the coordinate choice(s) on the model's ability to accurately represent the water mass distributions and three-dimensional circulation of the Atlantic. We performed several single-coordinate experiments, not only to illustrate the flexibility of the model, but also to bring forth some of the limitations associated with such a choice. Pure z-coordinate simulations showed the behavior described in Chassignet et al. (1996) for z-coordinate models, i.e. a warming of the deep ocean. MICOM mode simulations showed that the weak vertical discretization in unstratified regions did not permit a proper representation of the mixed layer physics.

We addressed one specific issue which is present in models such as MICOM or HYCOM that employ potential density either as the sole vertical coordinate or as one component of the hybrid framework: the question of how best to represent the potential density distribution throughout the entire oceanic depth range for a given reference pressure. The series of experiments demonstrated that a reference pressure at 2000 dbar indeed allow for a correct representation of the dense water masses that originate in Antarctica. When a reference pressure at the surface is used (sigma-theta), these water masses are characterized by an inversion in the vertical potential density profile which cannot be modeled. The addition of thermobaricity allowed us to quantify its importance on the surface and deep ocean circulations.

Part of our HYCOM development effort also consists of testing the code in idealized process oriented configurations. Most of our algorithm development work focused on developing and testing advection schemes for structured grid. The finite difference development revolved around testing and improving the tracer advection schemes in HYCOM. Four separate schemes were tested: a high order centered difference scheme combined with a flux corrected transport algorithm (CD-FCT) (Zalesak, 1979), the Upwind Third Order Polynomial Interpolation Algorithm (UTOPIA) (Leonard, 1995; Rasch, 1994), the MPDATA scheme (Smolarkiewicz et al., 1998), and the Weighed Essentially Non-Oscillatory (WENO) scheme (Shu, 1998). All schemes tested are conservative, and are at least second order accurate away from discontinuities and/or large gradients in the solution. CD-FCT and MPDATA revert to being first order accurate in the vicinity of discontinuities in order to enforce the monotonicity property; the Universal Limiter (Thuburn, 1996) was used to ``monotinize'' the UTOPIA scheme. WENO schemes are not strictly monotonic, but possess the Total Variation Bounded (TVB) property, i.e., the amplitude of Gibbs oscillations decays with decreasing grid spacing; WENO schemes eliminate the staircasing that plagues other monotonic schemes and extend the high order interpolation right up to the discontinuity.

The tests conducted were primarily idealized and geared towards process oriented studies (we also carried out a very limited number of realistic coarse resolution oceanic simulations). Our main conclusion is that higher order methods coupled to effective limiters are preferable to lower order methods, particularly during long integrations. In pure advection experiments, the higher order methods preserved the shape of the field better then their low order counterparts. In these experiments, the WENO schemes proved to be the most accurate, particularly when sharp fronts coexist with regions of smooth variations in the advective fields. However, they were also the most expensive since smoothness criteria had to be calculated; they are thus not recommended for operational use. The UTOPIA scheme performed best in terms of accuracy and computational efficiency; although it was a bit more expensive than CD-FCT, it did not exhibit its severe staircasing. MPDATA is similar in performance to UTOPIA, but was more CPU intensive.

A number of simulations were carried out to evaluate the numerical cabbeling induced by the advection scheme (Iskandarani and Chassignet, 2002). Cabbeling occurs when water parcels of similar densities, but differing T/S properties, are mixed and produce denser water. Cabbeling can be induced numerically by the diffusive processes inherent to the tracer advection schemes; this cabbeling is spurious and should be avoided where possible. The problem can be exacerbated in models that rely on non-linear advection schemes to enforce monotonicity, and where the amount of numerical diffusion grows whenever the limiters are activated. We reconfigured our pure advection test problems to process temperature and salinity fields that combine to produce a single density. For a linear equation of state with no physical cabbeling, the numerical cabbeling induced is very small to non-existent, depending on the advection scheme. The cabbeling in UTOPIA and CD-FCT was at the machine precision level; MPDATA produced a slightly larger error while WENO produced the largest error. The large error in WENO can be explained by the highly nonlinear nature of the scheme; nevertheless the error introduced was negligable. The situation is substantially different when a nonlinear equation is used: all schemes produced a finite amount of numerical cabbeling. UTOPIA's cabbeling however was the smallest by a factor of 3 compared to that of MPDATA, which produced the largest errors.

In order to perform real-time forecasting of 3-D Eulerian fields associated with such physical parameters as velocity, temperature, salinity, and density as well as Lagrangian trajectories, optimal and efficient data assimilation techniques are needed in addition to the ocean model and the data to be assimilated. The data assimilation techniques that have been evaluated, in MICOM and HYCOM, are: (1) an Optimal Interpolation (OI) scheme combined with a Cooper-Haines vertical projection of the surface information (see ONR report by O.M. Smedstad for details); (2) the Reduced Order Adaptive Filter (ROAF) (Hoang et al., 1997), which estimates unknown parameters by minimizing the forecast error; this technique requires the model's adjoint (developed and parallelized in collaboration with R. Baraille); (3) the Single Evolutive Extended Kalman (SEEK) filter (collaboration with P. Brasseur and J. Verron); and (4) a Reduced Order Information Filter (ROIF) of the Extended Kalman Filter (EKF) with a Gauss-Markov Random Field (GMRF) parameterization for the spatial covariances (Chin et al., 1999, 2001) which exploits the sparseness of the information matrix to dynamically update the forecast error covariance matrix (see ONR report by A. Mariano and T. Chin for details).

IMPACT/APPLICATIONS

This research has potential for providing the large scale information needed as boundary conditions for forecasting with regional coastal models.

TRANSITIONS

These results are being applied to the NOPP-sponsored HYCOM modeling consortium's effort to produce an efficient ocean forecast system for the Navy.

RELATED PROJECTS

Collaborations are active with scientists at NRL (H. Hurlburt, A. Wallcraft, P. Hogan, O.M. Smedstad) as well as with ONR sponsored PIs (M. Chin, A. Griffa, W. Johns, and A. Mariano).

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